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Continuously Tunable mm-Wave High Impedance Surface

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***Abstract*— A continuously tunable High Impedance Surface (HIS) is presented and experimentally demonstrated at approximately 60GHz. An optimized phase-shifting HIS consisting of a periodic surface placed over a ground plane is designed and employed to obtain the desired reflection phase. Tuning of the HIS is achieved by virtue of four compact piezoelectric actuators that produce a displacement between the two layers, when voltage is applied to them. This produces a continuous change of the reflection phase response of the structure. Simulated and experimental results are presented, demonstrating a dynamic surface impedance performance with a measured phase shift of over 200 degrees at about 60GHz.**

***Index Terms*—High Impedance Surfaces, Artificial Magnetic Conductor, piezoelectric actuators, reconfiguration.**

I. INTRODUCTION

HIGH Impedance Surfaces (HIS) have been extensively investigated for their property to provide an engineered reflection phase for impinging electromagnetic waves [1]. They typically consist of doubly periodic arrays of metallic elements placed over a ground plane. For a specific frequency they exhibit a reflection phase of zero acting as an Artificial Magnetic Conductor (AMC), but they can also be operated at various reflection phase values for different applications. They can be applied as ground planes in printed [1] or in cavity antennas for profile reduction [2], and they have also been employed for their phase shifting properties in applications such as reflectarrays [3], polarisation converters [4], holographic surfaces [5] etc.

Tunable periodic surfaces have attracted significant research interest and can be achieved with various techniques that dynamically change one of the surface's characteristics. Depending on the frequency regime various tunable components or materials have been employed thus far [6]. At lower microwave frequencies varactor and PIN diodes have been used for electronic tuning [6-8]. Nevertheless, their use has severe constrains at higher mm-wave frequencies due to losses, parasitic effects and non-linearities. At lower mm-wave frequencies Micro-Electro-Mechanical Systems (MEMS) have been successfully employed [9]. However, in order to obtain tuning, a MEMS component has to be integrated to each element of the periodic structure. This implies an upper frequency limit for the suitability of this technology, as the dimensions of the periodic elements decrease with the frequency, impeding the incorporation of an electrically large component in the unit cell of the array. Finally, tunable materials such as ferroelectric substrates [10, 11] at lower microwave frequencies and more recently liquid crystals [12, 13] at higher mm-wave frequencies have been investigated producing promising results. The main disadvantage of these tuning techniques is that they exhibit high losses and very low switching speeds (in the case of liquid crystals). Recently, piezoelectric materials and actuators have been proposed for the dynamic reconfiguration of phase shifting surfaces [14]. However, the proposed designs produced a limited theoretical phase shift of 125 degrees and the fabricated prototype incorporating only two piezoelectric actuators achieved a small measured phase shift of less than 30 degrees.

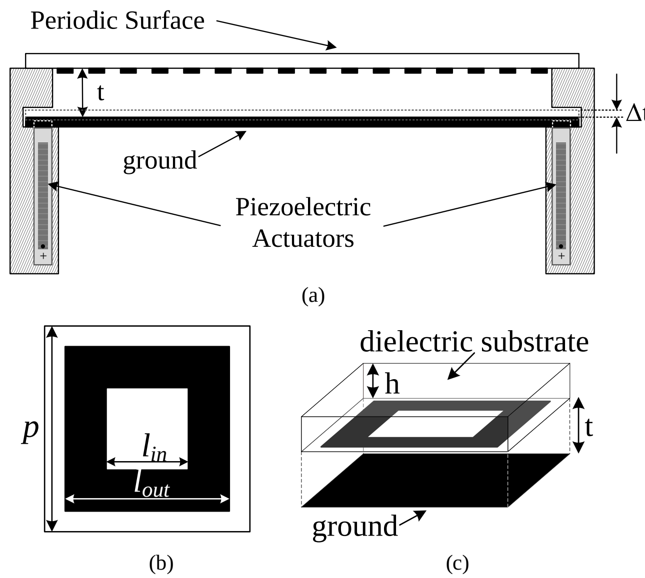

Fig. 1. (a) Schematic of the proposed tunable HIS with the supporting base (dimensions not to scale), (b) unit cell of the proposed periodic surface (top view), (c) unit cell of the proposed HIS (perspective view).

Here, we present a significantly improved design of a continuously tunable HIS achieving for the first time a measured phase shift of over 200 degrees at mm-wave frequencies (approximately 60GHz). The tuning is based on electromechanical reconfiguration obtained by the use of four piezoelectric actuators integrated within the HIS supporting

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structure. The actuators exhibit a displacement under a voltage bias which is translated to a dynamic control of the reflection phase. The piezoelectric actuators are characterized by high accuracy and reliability for nano-positioning, low voltage operation and fast response in the order of microseconds. The proposed structure is presented in Fig. 1(a). It consists of a periodic surface placed above a ground plane a distance *t*, creating an air cavity. Simulation and measurements results are presented and are in very good agreement. Finally, an assessment of the losses is presented demonstrating the potential for achieving low loss tunable HIS at mm-waves.

II. Design of Tunable HIS Structure

The unit cell of the proposed structure is depicted in Fig. 1(b, c). The structure is formed by the periodic surface and the ground and acts as a HIS reflecting the impinging waves with zero phase shift at a specific frequency and a wide range of reflection phases at other frequencies. In typical implementations of HIS structures, the substrate is grounded, creating a dielectric filled cavity between the array and the ground plane. Nevertheless, in the proposed configuration an air cavity is created giving an extra degree of freedom for controlling the HIS reflection phase response which is strongly related to the cavity thickness. Consequently, tuning of the reflection phase can be obtained by mechanically changing the distance between the ground plane and the periodic surface. For a continuous tuning of the reflection phase, four piezoelectric actuators are employed supporting the four corners of the ground plane. Biasing the actuators induces their vertical expansion which is translated to a movement Δt of the ground plane (Fig. 1a). The cavity thickness is subsequently decreased, changing the reflection phase response of the structure. A plastic supporting base is used to hold in place the four actuators, and the two surfaces. It should be noted that the actuators are positioned below the ground thereby not interfering with the reflected radiation.

The maximum tunability of the presented concept depends largely on the maximum achievable displacement from the piezoelectric actuators. The piezo-actuators proposed for the design under investigation, are commercial actuators (see Section III) with a length of 18mm and can achieve a nominal maximum displacement of 18μm for an applied voltage of 120V.

Based on the information of the actuators' displacement, the unit cell of the structure has been designed, choosing the geometry and dimensions so that a maximum phase shift could be obtained from the structure by changing the actuators' biasing voltage. A square loop element has been selected for the HIS array, due to the fact that it provides a fast variation of the phase of the reflection coefficient with frequency [15]. The elements were printed on a dielectric substrate with ε_r=2.2, $tan\delta$=0.0009 and thickness h=0.8mm (Fig. 1c). The dielectric substrate is placed on top of the array as this was found to minimise the losses. The periodicity and the dimensions of the unit cell are p=1.75mm, l_{out}=1.5mm and l_{in}=1mm, as shown in Fig. 1(b). The reflection magnitude and phase of the proposed configuration have been extracted using CST Microwave Studio™ simulation software, applying periodic boundary conditions at the unit cell in order to evaluate its tunability.

The simulation results for different cavity thicknesses from t=2.65mm to t=2.62mm are presented in Fig. 2. It can be observed from Fig. 2(a) that high reflectivity values, and hence low losses, are obtained with the proposed design. Moreover, as shown in Fig. 2(b), a significant phase shift is achieved, with a maximum of $\Delta\varphi_1$=217° at 58.14GHz for a displacement Δt=20μm, which is close to the maximum displacement the selected actuators can produce. From the same figure it can be observed that with the use of a different actuator, providing a displacement of Δt=30μm, a maximum phase shift of $\Delta\varphi_2$=262° can be obtained at 58.25GHz. It should be noted that the achieved phase shift is significantly higher (approximately doubled) than the simulated phase shift obtained in [14]. The reflection phase at the point of maximum slope is not close to 0° as would be typically expected by an HIS surface, but ~ −150° due to the fact that the reference plane is taken at the top of the dielectric substrate.

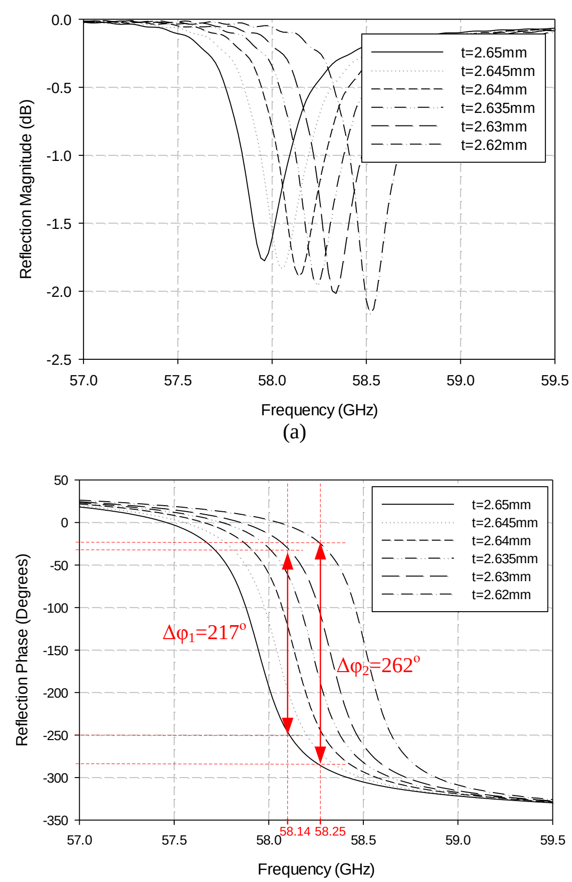

Fig. 2. Simulated reflection characteristics of the proposed periodic surface for different cavity thickness (2.62mm–2.65mm): (a) reflection magnitude, (b) reflection phase.

III. Fabrication and Measurements

A prototype of the proposed structure has been fabricated and measured to validate the simulation results. A schematic of the measurement setup is shown in Fig. 3(a). The periodic array that has been used for the measurement (Fig. 3b) consists of an array of 46×46 copper square loop elements printed on a 0.8mm thick, TLY-5 Taconic™ substrate with overall dimensions 100mm×100mm (~20λ×20λ). A supporting base made of plastic acetal copolymer (POM) material has been fabricated in order to support all the individual components of the proposed structure as shown in Fig. 3(c). The periodic surface has been positioned on the supporting base, on top of the ground plane which in turn is supported by the four piezoelectric actuators (Fig 3c). The actuators have been placed in specially designed openings within the four vertical posts of the base, which also include the necessary gaps to provide access for the electrodes connected to the actuators.

A. Piezoelectric Actuators

The piezo-actuators proposed for this application, are commercial actuators built by placing thin Lead (Pb) Zirconate (Zr) Titanate (Ti) (PZT) ceramic disks on top of each other forming stacks [16]. The ceramic disks are separated by thin metallic electrodes, which are used to apply the necessary voltage on each ceramic disk. The material used for the fabrication of the disks has the property of expanding vertically when exposed to an electric potential, due to the inverse piezoelectric phenomenon. The displacement of the actuators is a function of the applied electric field strength, the length of the actuator, the forces applied to it and the properties of the piezoelectric material used. The maximum operating voltage is proportional to the thickness of the disks while the total displacement of a piezoelectric actuator is proportional to its total length [16].

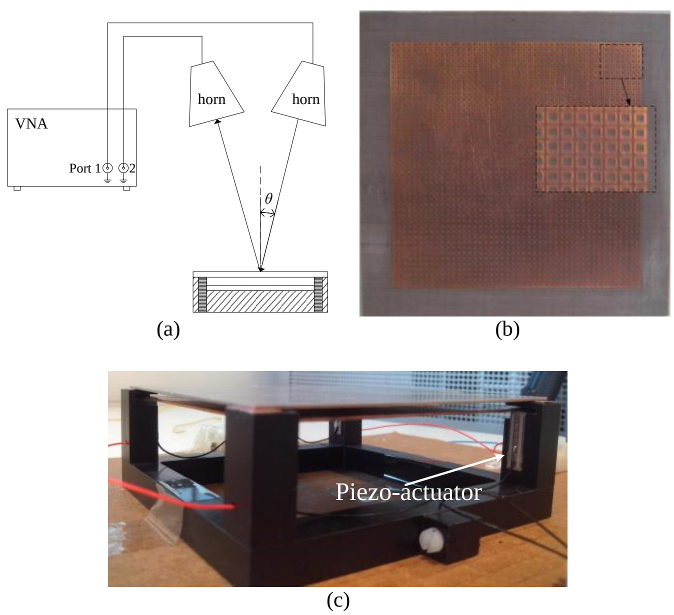

Fig. 3. (a)Schematic of measurement setup and, photograph of (b) the fabricated periodic surface and (c) the complete structure with the supporting base and the actuators.

The main advantages of using the specific piezoelectric actuators are their low-cost, high accuracy and reliability for nano-positioning, low voltage operation and finally their fast response which is in the order of microseconds. The lifetime of the actuators is in the order of 10^5 hours for DC operation.

The actuators used in the measurements were the P-885.51 from Physik Instrumente™ (PI). Their length is 18mm and can achieve a nominal maximum displacement of 18μm for an applied voltage of 120V. Two electrodes are connected on either side of each actuator to the metallic sections (shown in the photograph) used to provide the DC bias.

B. Measurements of the Fabricated Prototype

Two V-band horn antennas were used for the measurement of the reflection characteristics of the fabricated prototype shown in Fig. 3(b). The measured reflection phase for different actuation states (V=0V–120V) is presented in Fig. 4(a). The measurements presented are normalized with respect to a measurement of just a planar metallic surface placed at the same position as the array. A maximum phase shift of 200.5° is obtained at about 58.14GHz, validating the simulated performance of the proposed design. The measured reflection magnitude and phase versus the DC voltage are also depicted as an inset in Fig. 4(a) for the frequency of the maximum phase shift. It can be observed from the graph that the phase changes almost linearly with the applied voltage. However, the reflection magnitude is lower than expected from the simulation results. This is studied and explained in detail in section *C.* Moreover, a comparison between full wave simulation results and measurements is carried out in Fig. 4(b) for V=0V and V=120V, corresponding to cavity thicknesses t=2.648mm and t=2.63mm respectively, i.e. to a displacement Δt=18μm. The maximum phase shift obtained from the simulation for the specific displacement is 208.57° at 58.16GHz. It is evident that there is good agreement between the measured and simulated results. The small discrepancies and fluctuations observed in the measurements are due to the fact that the dielectric substrate used for the periodic surface is not perfectly flat and therefore it was not exactly parallel with respect to the ground during the experiment.

C. Effect of Copper Conductivity

Although the measurement results have validated the proposed concept in terms of the achieved phase shift, it can be observed that the measured reflection magnitude is lower than that expected from simulations. This is attributed mostly to the reduced conductivity of the printed copper elements on the specific substrate experienced at these frequencies. The reduction of the conductivity occurs because of the roughness of the copper surface. Due to the resonant nature of the proposed structure and the strong currents induced on the elements, the ohmic losses are significantly increased with decreased copper conductivity. Indeed, simulations have been carried out for reduced copper conductivity and for t=2.64mm, corresponding to approximately 90V DC bias of the actuators during measurements, presented in Fig. 4(c). The simulations show that while a 100% conductivity (5.96×10^7 S/m) gives a reflection magnitude of only −1.83dB, a 50% conductivity (2.98×10^7 S/m) results in a reflection magnitude of −2.62dB, and a 25% of copper conductivity (1.49×10^7 S/m) gives a reflection magnitude of −3.7dB.

Based on [17] a surface roughness of 3μm results in 25% of the ideal copper conductivity and even if the roughness is increased, the value of conductivity is not further reduced.

Thus, some of the additional losses (about 7dB) exhibited in the measurements should be attributed to the imperfect flatness and variable thickness (~6%) of the substrate of the periodic surface which caused energy loss due to reflections in other directions. Nevertheless, these problems could be eliminated by using better quality materials such as optically flat quartz substrate and fabrication processes appropriate for high mm-wave and submm-wave frequencies [13].

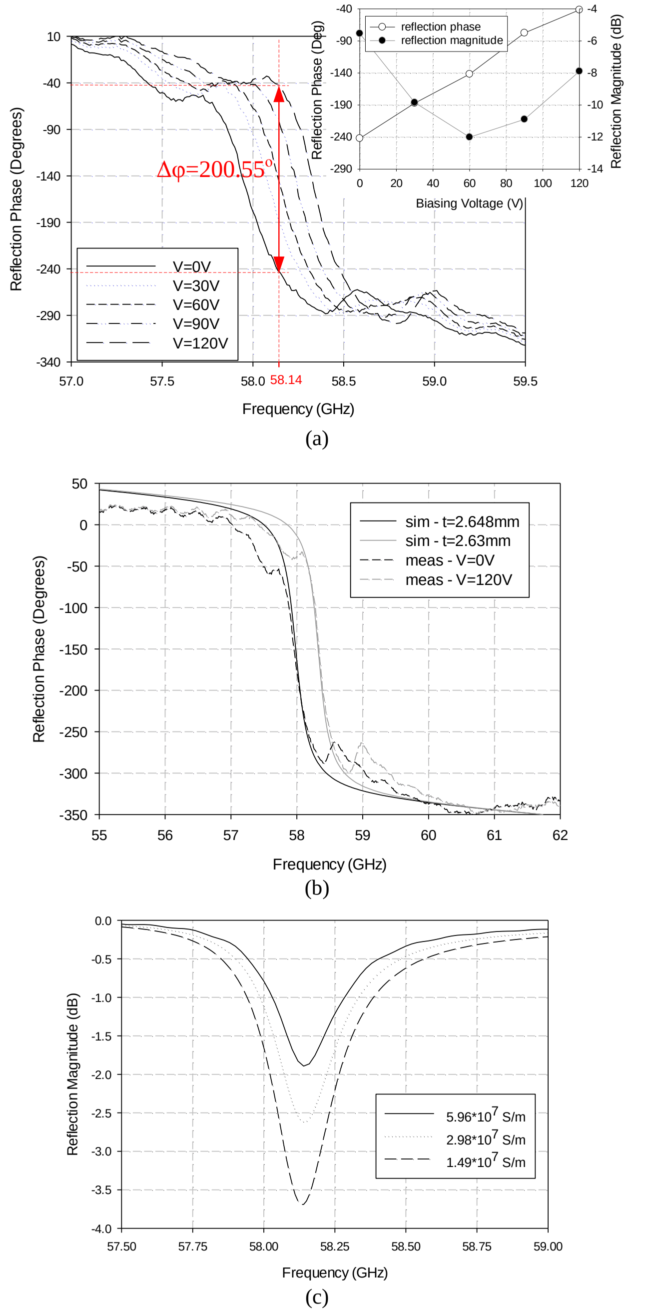

Fig. 4. (a) Measured reflection magnitude and reflection phase for different voltages, (b) Comparison of simulated and measured reflection phase for V=0V and V=120V and (c) Simulated reflection magnitude for t=2.64mm for different copper conductivity values.

IV. Conclusion

Continuously tunable low-loss HIS type phase shifting surfaces based on piezo-actuators have been demonstrated through simulation and experiments giving a measured phase shift of over 200° at 58.14GHz. The proposed technique is directly scalable to higher mm-wave and submm-wave frequencies, where more phase shift could be obtained with the same or even less available displacement, paving the way for the realization of a new class of tunable quasi-optical components.

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